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A New Simulant to Represent The Silicate Interior of Enceladus

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Introduction: Hypothetically, Enceladus is a habitable environment: there is a global sub-surface ocean [1], potential hydrothermal activity [2], and bio-essential elements have been detected within the plumes emanating from the South Polar Region (SPR) [3]. Understanding this environment, and the reactions occurring within it, will further our understanding of its potential habitability. However, this relies on assumptions about the physical and environmental conditions, including the composition of the silicate postulated to be at its core. Here, we present an evaluation of the possible silicate composition, including organic materials. From this evaluation, a new simulant to represent this silicate has been designed, which can be used in simulation experiments and modelling of the Enceladus interior.

Current understanding of the silicate interior: Evaluation of the interior of Enceladus can only be achieved through assumptions and from the indirect measurements of the plumes made by the instruments onboard Cassini, predominantly INMS and CDA [4-6]. The detection of SiO₂ nanoparticles within the plumes infers a silicate interior [2], however the precise composition of the silicate is not confirmed. Analysis of particles within Saturn's E-ring and the SPR plumes suggests that the silicate contains Mg-rich, Al-poor minerals [4] and organic species [5,6]. Molecular hydrogen has also been identified within the plumes [7], which may infer that serpentinisation reactions occur at the rock-water interface, for example between olivine and the sub-surface ocean. The extrapolated silicate composition from these data is one equivalent to a carbonaceous chondrite-type meteorite [8-10].

The modelled core density is approximately 2.4 g km⁻³ [11], which has led to the assumption that the interior is porous, unconsolidated and has not experienced significant melting [12, 13]. Further to this, a porous interior increases the relative surface area exposed to the sub-surface ocean, increasing the rate of water-rock interactions. This supports the likelihood of long term water-rock interactions that will have altered the silicate chemistry and mineralogy [8, 9]. However, the detection of both the SiO₂ particles and hydrogen within the plumes suggests the silicate is not fully hydrated and that these processes continue today [7, 9].

Simulant design: To satisfy the compositional requirements, we have based the silicate composition on the chemistry of CI carbonaceous chondrites, which display extensive aqueous alteration and contain up to

20 % water [14]. Further to this, the grain density of a CI chondrite (2.42 ± 0.060 g km⁻³) [15] is comparable to the modelled silicate density of Enceladus.

Inorganic: To acquire the best representation of a CI chondrite, the average chemistry of the three most widely studied CIs (Ivuna, Orgueil and Alais) was calculated (Table 1).

Table 1- Comparison between the calculated average CI composition and the chemistry expected for the final simulant based upon the ratio of minerals selected.

Oxide	Average CI composition (wt %)	Expected analogue composition (wt %)
SiO ₂	27.96	27.62
FeO	10.47	11.90
Fe ₂ O ₃	11.63	10.52
SO ₃	5.23	5.76
MgO	17.83	17.45
Al ₂ O ₃	2.15	2.12
Cr ₂ O ₃	0.60	0
Na ₂ O	0.43	0.11
K ₂ O	0.20	0
P ₂ O ₅	0.09	0.42
TiO ₂	0.07	0.003
CaO	0.41	0.73
MnO	0.17	0.01
NiO	2.00	2.17

To replicate the composition of a CI chondrite as accurately as possible, minerals were used (as far as possible) that have previously been detected in CI chondrites [16, 17] (Table 2). The chemistry expected, based upon average mineral compositions, was compared to the calculated average CI composition (Table 1). The maximum variation between the calculated composition and the expected composition is 1.5 wt%.

Table 2- The proposed mineralogy for the silicate simulant based upon the chemistry for a CI chondrite.

Mineral	Weight %
Olivine (9:1 Fosterite:fayalite)	15
Magnetite	15
Serpentine	15
Almandine	10
Diopside	5
Talc	5
Quartz	5
Pyrite	3
Anhydrite	1
Apatite	1
Dolomite	1
Bruennerite	0.15
Calcite	0.02

Carbon chemistry: In line with the chemistry of CI chondrites, our simulant needs to contain approximately 3 wt% carbon [18], in both inorganic and organic form. Dolomite, bruennerite and calcite (Table 1) have all been detected in CI chondrites [19] and can be used to represent inorganic carbon. Other forms of carbon, nanodiamonds, silicon carbide and graphite are present in very small concentrations in CI chondrites, but because of the conditions that are expected to occur on Enceladus at the rock-water interface, these components are not expected to react. Therefore these will be omitted from the simulant.

Organic molecules in CI chondrites are predominantly present as the ‘macromolecular material’, which predominantly consists of a high aromatic structure. This constitutes 70% of their organic fraction [see 20 for a review]. Until recently, only short chained hydrocarbons had been detected in Enceladus’ plumes, however data from Cassini’s CDA and INMS instruments have indicated organics with masses of up to 200 au (the limit of the CDA) [21]. This has led to the assumption that the silicate interior likely contains large macromolecular organics, predominantly composed of discrete benzene-like sub-structures connected through non-carbon functional groups or dehydrogenated carbons [21]. Although similar to chondritic macromolecular material, its structure is less aromatic and contains shorter bridges between the aromatic structures. Terrestrial kerogen has been used as an analogue for chondritic organic material [e.g., 22] but also has a greater predominance of fused aromatic rings bridged

by long carbon chains, and so does not represent a good analogue for Enceladus’ organic matter.

Enceladus’ organic fraction will therefore be represented in the simulant by humic acid. Its structure is predominantly discrete benzene subunits connected through dehydrogenated carbon bonds or through functional groups. It is also more readily available.

Production: The simulant is in the process of being finalised and produced. Currently, test samples of each mineral have been characterised; these results are currently being analysed to recalculate the ratio of minerals required based upon specific mineral samples. Bulk samples will be purchased, prepared and mixed, and then further characterisation of the final simulant can be conducted. This final chemistry will be presented.

Uses: The simulant will be used to replicate the sub-surface environment of Enceladus in simulations of the reaction cycles occurring at the rock-water interface.

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